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Cooling and heating energy performance of a building with a variety of roof designs; the effects of future weather data in a cold climate

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ABSTRACT

Building engineers commonly use the Typical Meteorological Year (TMY) weather data for simulation and design purposes. However, the nature of TMY in excluding weather extremes makes them less suitable to investigate the effect of potential climate change on building design as climate change likely increases the frequency and magnitude of those extreme conditions. The current practice of designing buildings has lacked a clear method to incorporate future climate change trends. An approach is used to compare present weather simulation results of a commercial building with varying roof reflectance and insulation thermal resistance parameters with future year-by-year results which are affected by potential climate change. Future weather data for year-by-year simulations is obtained by “morphing” historical weather data with a General Circulation Model (HadCM3). Mean energy consumption and optimal roof configurations are discussed with regards to climate change over the study period, and are compared to results obtained with TMY data. Results show that increased roof solar reflectance always lead to less mean and less variant cooling energy consumption. The study shows the importance of considering possible future climate scenarios and in building energy performance design.

1. Introduction

Over the past decades, literature has indicated that a warming global climate is affecting various human activities ranging from crop production [1] to power plant output [2]. The practice of designing buildings to cope with potential climate change has lacked a clear method to incorporate this trend. Today's buildings are designed to last several decades, and as weather patterns change over time, buildings designed for today's climate may not withstand the potential changes during their useful lives.

Building designers should therefore take future climate predictions into account when assessing building energy performance in the subsequent building design process. Most building energy simulation packages are use weather data which represents a single, typical meteorological year (TMY). The implications of this practice are twofold. a) extreme weather conditions are excluded from the TMY weather data, and the use of TMY data might not be able to reflect future realities since the weather tends to become more extreme under the premise of climate change [3] and b) regardless of the different climate change scenarios, year-to-year changes in the weather might not be adequately captured by a single TMY.

Therefore, even if building engineers today commonly use TMY weather data for design and analysis purposes, such data can not only lead to an under- or overestimation of energy savings, but also does not support future weather modeling.

In this optic, the objective of this research is to:

1. Quantify and systematically demonstrate the effects of future climate changes on energy consumption.
2. Offer a path to building design which considers the effects of climate change.

This research described in this paper seeks to accomplish this objective by improving the thermal design of roofs in cold climates to reduce overall yearly energy consumption by anticipating the predicted effects of future climate change. Two factors inflecting roof design are studied: thermal insulation and solar reflectance. Simulations are conducted for several combinations of the two factors in order to comprehend underlying synergies and trends.

1.1. Climate change and its impact on building energy performance

Jentsch et al. [4] discussed the fact that many currently used TMY weather files for building energy performance are typically derived from historical weather data from the latter 20th century, and research by [5,6] has demonstrated that there exists discrepancies between this data and current weather trends. In Canada, the same issues arise from the use of Canadian Weather Year for Energy Calculation (CWEC) data

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[7], which is derived from historical weather data from 1961 to 1990. With the now widely accepted effects of climate change, the amount of energy used for building cooling should increase in the future. This is supported by the U.S. Global Change Research Program, which states that "warming will be accompanied by decreases in demand for heating energy and increases in demand for cooling energy. The latter will result in significant increases in electricity use and peak demand in most regions" [8].

While heating buildings can be achieved by using various energy sources at high efficiency, most commercial cooling devices operate solely on mechanical power, but several advances in passive cooling may be used to shift the cooling load to other measures [9] and the combination of various materials and colors and structure weights on roofs [10] Furthermore, an increase in global air and water temperatures will tend to reduce the overall output of traditional electricity generating plants, as the efficient output of power plant cycles are dependent on low condenser temperatures and large water flows [2]. This situation could create a stacking problem in which peak demand for electricity could rise while power plant output could decline. Cooling systems involve the displacement of heat from one medium to another and are evaluated on their coefficients of performance (COP). For this reason, reductions in heating loads and increases in cooling loads will affect overall energy consumptions differently.

1.2. Climate change prediction models and their implication on building energy simulation

Building energy simulations involve hourly step calculations which reflect the complex interactions between HVAC systems, control systems, internal loads and external factors. Building energy simulation programs are commonly used to quantify the savings and/or penalties for a variety of techniques used to improve energy efficiency and to estimate the monthly and annual energy consumption of buildings. However, this quantification, might not be reliable due to a deterministic approach in simulation. Estimated energy performance based on typical meteorological years (such as TMY) and weather years for energy calculation (WYEC) may not reflect actual energy performance and their variations. In addition, TMY does not capture extreme weather conditions. Given the stochastic nature of building operation and weather patterns, exact predictions are difficult, if not impossible, to obtain. Furthermore, research by [11] documented that the city built environment and heat islands pose effects on the temperature and humidity of the surrounding environment, and suggests that these factors must be included in weather data for building simulations by using an urban downscaling methodology.

Researchers have increasingly been using General Circulation Models (GCMs) to predict future weather patterns affected by climate change. So far, several methodologies have been developed to integrate these predictions into weather files which is used to reliably prepare for the eventuality of climate change [12–14]. Jentsch et al. [15] discussed the importance of climate change adaptability in planning for future climate scenarios into the widely used TMY2 weather file formats. They chose to use the Hadley Center Coupled Model, version 3 (HadCM3) to predict future weather conditions, accounting for the effects of climate change. Instead of representing data predictions for a single weather station at a specific geographical location, the HadCM3 model covers a finite grid point model covering an area of 2.5° latitude by 3.75° longitude, with a resolution nearing $300 \times 300\,km^2$ worldwide. To measure the model's performance, Samadi and Sagareswar [16] compared correlation and frequency analyses of precipitation and temperature data from four GCM (GDFL, CCSNIES, HadCM3 and CSRIO) for Kermanshah, Iran over a 30-year period, and determined that HadCM3 predictions were significantly closer to real observations in both cases. They found that HadCM3 presented less uncertainty in results compared with the other GCMs (as a percentage of error) and was therefore found to be more reliable overall, especially in winter considering the presence of local factors. They indicated that this was the case in most other research papers. However, general circulation models such as HadCM3 provide monthly data whereas hourly data is required in building energy simulations. A downscaling method should be applied to fine-tune to the required resolution. Jentsch et al. [9,15] proposed using 'morphing' techniques to generate new TMY2 files from current Test Reference Years (TRY) and Summer Design Years (DSY).

With morphing methodology, originally developed by Belcher et al. [17], corrections for future hourly temperature, humidity and solar radiation GCM data are simply superimposed on existing EPW (EnergyPlus Weather) data. A modified weather file is generated which can be used by building designers with tools that are available in the public domain. While this method represents an improvement over using TMY data for current or future year building energy predictions, some researchers [18] acknowledge that more accurate and distinct future weather data files need to be generated to adequately reflect future climate conditions.

Zhu, et al. [19] applied the TMY morphing method to three cities in China over five future periods ending in 2089, and showed that average increases in temperature ranged from 3.0 °C to 5.4 °C in all three cities.

In their analysis of a "Passivhaus", or low energy design, McLeod et al. [20], determined peak load data from the worse of two distinct winter weather situations from a "morphing" method used with the Hadley Center Regional Model 3 (HadRM3) GCM, which they have encapsulated in a software conveniently named the Passivhaus Planning Package (PHPP12).

Kikumoto et al. [14] proposed an improved method for obtaining future weather data by using a method referred to as "dynamical downscaling". The often used "morphing" method, the authors argued, causes much data to be lost due to the GCM's coarse resolution. It was also stressed that statistical manipulations led to the loss of information concerning interactions between various weather components, which is particularly important in determining extreme weather conditions. Boundary conditions originating from GCM data for prediction year climates are used to define a Regional Climate Model and the data is dynamically downscaled to produce weather predictions and standard data which can be used to simulate a building in the predicted climate for the year in question. The authors created a Weather Research and Forecasting (WRF) model for the 2030's, which they used to conduct accurate predicted future building energy calculations in a simulated detached house, with room for improvements in accuracy and bias mitigation. The downscaling methodology was also used in a point-based stochastic weather generator (WG) by Forsythe et al. [21] to demonstrate its efficacy for the Pakistani Upper Indus Basin.

Caraway et al. [22] developed another future weather model generation technique based on cluster analysis and k-nearest neighbour time series resampling. This is achieved by clustering locations into homogeneous regions by comparing historical seasonal precipitation patterns, by analyzing Markov transition probabilities to correlate precipitation occurrence and by applying a k-nearest neighbour (K-NN) weather bootstrap, the latter being a method developed by [23] in which data showing days which resemble the simulated day are assigned higher probability in the predicted weather file.

1.3. Adapting building design processes to adapt to climate change

With regards to the environmental or economic strategies surrounding the design and usage of buildings over their useful lives, climate change presents building designers with added constraints. Designers who do not take future conditions into account risk presenting future owners or occupants with buildings which might not effectively respond to local environmental conditions at some point in time. Therefore, the focus of any climate adaptive design will be to analyze the energy patterns of a building with different simulations using weather predictions which span over this period [24].

The simplest energetic strategy to implement could be the one

which produces the least deviations from normal conditions, but economic factors or business cases could make other strategies, such as retrofitting, more appealing. Loonen et al. [25] discussed the idea of a Climate Adaptive Building Shell (CABS), which was defined as a building which could “repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions with the aim of improving overall building performance”. Robustness, adaptability, multi-ability and evolvability were defined and placed into context for energy efficiency. While their definition is not specifically geared towards global climate change, it does provide a blueprint towards defining building adaptability to varying indoor and outdoor conditions.

Robert and Kummert [26] generated future weather files to investigate if they affected the energy performance of an existing Net Zero Energy Building (NZEB) home in the northern climates of Montréal,QC and Massena, NY, and they found that the building does not attain net-zero energy status in future years. This has led to the argument that NZEB buildings should always be designed with weather data spanning over their entire useful life instead of with TMY data which might not even adequately reflect the first year of operation. In the same vein, McLeod et al. [20] argued that special attention needed to be placed on accurate local climate data to make Passivhaus designs relevant, data which is further complicated with climate change. For these specific cases, they considered that overheating and undercooling posed a significant risk to the mission and certification of the building.

To allow designers to evaluate the probability that predicted future climates will cause buildings designed for the current climate to overheat, Jenkins et al. [27] performed regression analyses on building simulations using weather files which were generated with the UKCP’09 Weather Generator. Weather variables (total hourly precipitation, mean hourly temperature, vapor pressure, relative humidity, sunshine fraction, downward diffuse radiation and direct radiation) were generated on a monthly, daily or hourly scale from 3000 equally probable climate years. These simulations were taken from real-case studies and from previous simulation studies. Results showed a moderate future probability of overheating, and ideas on integrating this type of risk analysis in current design practice were discussed.

1.4. Effects of highly reflective roofs (cool roofs) on buildings

The practice of installing cool roofs (surfaces which highly reflect solar radiation back to sky) in various climates have existed for millennia, as white roofs are very prevalent along the Mediterranean and in the Middle East. As effective as they are, they have only been sparsely used in western architecture. However, as techniques used to improve comfort have progressed, cooling has become as equally important to building design as heating is. Since buildings are static structures that cannot easily be adapted to changing seasonal weather patterns, a balance must be found to smooth power demand and limit energy consumption throughout the year while taking advantage of the conditions present in the natural surroundings. Such a balance will often be unique to every type of building in every climate.

In hot environments, while limiting heat gain and increasing reflectivity on the roof can passively serve to increase comfort when outdoor temperatures are high, such measures can also serve to reduce cooling loads from air-conditioning devices. In the United States, the Department of Energy (DOE) began investigating the benefits of cool roofs in the 1980's, which were favorably adopted in California at the beginning of the 21st century as a method to reduce peak demand from air conditioning in the summer following an energy crisis. Several years later, such practices have become more common, with dedicated organizations such as the Cool Roof Rating Council making their appearance as a measure in green building certifications, such as LEED accreditations.

Currently, for a roof to be defined as a “cool roof”, it must possess a high solar reflectance factor of 0.55 after 3 years of use, effectively returning a majority of the solar radiation hitting the roof back to the sky in the form of infrared radiation [28,29] although technology helped to produce dark-colour less reflective cool roofs [30]. Several studies have been made to determine deciding factors on their usability for various buildings particular climates. Piselli et al. [31] studied the use of cool roofs on buildings in five Italian climate zones with varying occupancies, building characteristics and HVAC systems, using optimized solar reflectance factors to minimize the energy consumption of the buildings. Their results showed that for warmer climates, the maximally considered solar reflectance of 0.8 was the optimal value. However, for heating dominant regions, the optimal solar reflectance depended on other parameters, such as the characteristics of the HVAC system. Furthermore, [32] devised a simple calculator to assist designers in determining the benefits of highly reflective roofs in varying conditions, while [33] proposed an advanced model which correlated daily accumulative inward heat in buildings with rooftop albedo, mentioning that increasing roof insulation can curtail air-conditioning requirements in the summer.

Several studies were conducted to determine the effects of varying albedo on roofs and their surroundings. A series of experiments were conducted by [34] to measure heating and cooling energy demand changes with varying roof albedo in various conditions and were validated with TRNSYS simulations. The authors found variations in reductions in air temperatures and overheating hours, increased heating loads, and decreased cooling loads. Touchaei et al. [35] found that increasing the solar reflectance of surfaces such as roofs, walls and pavement in urban settings located in cold climates reduced solar heat gains in buildings and modified surrounding meteorological conditions. A DOE-2 building simulation was used to simulate four prototype commercial buildings with varying roof definitions: a dark roof control design, a white roof control design, and an albedo-enhanced roof. While calculating the difference in yearly heating and cooling energy consumption over white and albedo roof scenarios, it was found that the cooling energy savings from the white control roof cancelled the heating energy penalties for small offices and that heating energy losses from albedo-enhanced roofs outweighed cooling savings. However, as the size of the office building increased, cooling energy savings from white or albedo-enhanced roofs surpassed heating losses, and thus their presence became justified.

Beyond reflectance, increasing the thermal resistance of insulation on roofs to reduce energy consumption in the heating season, which is not specifically defined but which generally runs from October to May, can lead to contradicting effects during the cooling season, which generally runs from July to September. The minimal required total Thermal Resistance (RSI value) of insulation in buildings suggested by the national building codes for Montreal is $5.4\,m^2K/W$. An experimental study conducted by Ramamurthy et al. [36] concluded that extra insulation on the roof might not always be beneficial during the cooling season, as heat accumulating inside a building can be prevented from exiting a highly insulated roof.

On its face value, the decision to use cool roofs in cold and northern climates may seem counterproductive due to the advantages obtained from solar heat gains in the winter. However, this is misleading. The presence of snow in most of the heating season, narrowed sun ray angles radiating during shorter days, increased cloud cover and nighttime heating schedules all contribute towards minimizing the impact a cool roof would have in preventing winter heat gains in the building. The effects of snow accumulation on cool roofs were studied by [37–39], who concluded that its presence significantly mitigated their heating penalty in the winter in both Montreal, QC and Anchorage, AK. Considering that weather patterns are dynamic and often deviate from standard definitions, roof design practices for winter remains largely unchanged due to the permanent factors discussed above. While predictions show that the length of the annual snowfall period will decrease with a warming climate, the frequency of heavy snowfall events

have been increasing of the past 30 years and it is estimated that it the trend should continue in the foreseeable future [40].

Building enclosure materials lose their performance over the years as a result of weathering and ageing. Longevity study of cool roofs [41,42] contributed to the production of durable cool roofs with solar reflectance ranging from 0.3 to 0.85 and thermal emittance ranging from 0.8 to 0.9 showing minimum degradation [43–46]. The effects of using cool roofs to reduce the energy consumption of buildings have been widely conducted with both previous and current weather conditions. However, considering the effects of climate change, the literature shows that, compared to previous years, warmer summers and winters with reductions in solar irradiation in the winter and increases in the summer, are expected in future years [26]. These variations can affect the energy performance of reflective roofs. Therefore, future weather data that accounts for the effects of climate change is used to demonstrate the energy performance of a variety of roof designs for the future.

2. Methodology

2.1. Adaptation of a climate change model to a base case building

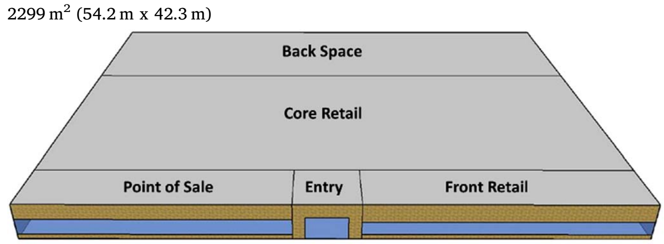
To evaluate the effects of present and future weather conditions on a particular design, one of the building scenarios that was previously used in [7,35], a one-storey commercial building with a 2299 m^2 floor area and a flat roof, was modeled with varying thermal resistance insulation and solar reflectance values. The DOE prototypical retail store reference building geometry and its characteristics are also available on the U.S Department of Energy website [47]. The original building enclosure characteristics are adapted to ASHRAE standard 90.1, upgraded to the Canadian National Energy Code for Buildings (NECB, 2011) since the case study is located in Montreal, Canada. The building is defined as having five zones (core, front, back space, point of sale, entry) and no plenum. This building model has been defined with 126 different roof configurations. The layout and overall characteristics of the building are summarized in Table 1.

EnergyPlus [48] is used in this paper to simulate building energy consumption. Total heating and cooling loads per unit area have been simulated for every simulation year over a lifespan of 20 years which begins in the year 2018. To reflect actual building energy consumption, a previously introduced COP of 2.93 has been applied to the cooling load to calculate cooling energy consumption, and the heating source for the building is assumed to be entirely electric, with an efficiency ($\eta_{heating}$) of 100%. Therefore, final results do not represent physical quantities of thermal energy, which in theory would negate each other, but instead represent the total yearly mechanical-electrical energy consumption required to heat and cool the building. While this assumption may not accurately predict the end-use electricity consumption, it is a common and acceptable method for estimation purposes. The reason behind this method is twofold. Firstly, determining HVAC system consumption in simulations requires much greater simulation resources. Secondly, depending on the building enclosure configuration (roof design), the size of the required HVAC system could change, leading to variations in HVAC efficiency, affecting HVAC efficiency and therefore results, which is outside the scope of this study.

2.2. Future hourly weather generation

Six future possible scenarios relating to population of the world, economic condition, and the technology are introduced in the third and fourth reports from the IPCC (Intergovernmental Panel on Climate Change) [49]. Each of these scenarios predict that a specific quantity of greenhouse gas emissions are released up to the year 2100, based rely on data collected in the 80 s and 90 s. In the A2 scenario, the global population continuously increases, economic development is primarily regionally oriented, and capita economic growth and technological change are slower than in other scenarios. Additional information on these scenarios can be found in [15]. In this study, the A2 scenario is used as a representative of future years. World temperatures can increase or decrease in line with the greenhouse gas emissions presented by this scenario. Many other parameters can be affected by these changes, such as solar radiation, wind speed, cloud cover and relative humidity. Therefore, a general circulation model is required to mathematically predict such alterations. HadCM3, a general circulation model, covers grid points not only for Montreal, Canada, but over the entire planet. Since data from a general circulation model is limited to

Table 1
Building characteristics used for simulation.

Item	Descriptions
Form	
Total Floor Area	2299 m^2 (54.2 m x 42.3 m)
Building shape	
Window-to-Wall Ratio (WWR)	25.4% on the south facing facade
Envelope	
Exterior walls	
RSI-value (m^2K /W)	4.1
Solar reflectance	0.7
Roof	
RSI-value (m^2K /W)	2.4–15.4
Solar reflectance	0.1–0.9
Window	
RSI-value (m^2K /W)	0.5
SHGC	0.3
Foundation	
RSI-value (m^2K/W)	5.9
Air Barrier System	
Infiltration	0.001024 $m^3/s{\cdot}m^2$ of above ground envelope surface area

monthly averages, a downscaling method must be applied to convert the monthly averages to the hourly data required to use building energy simulation programs. In this paper, the typical meteorological weather file (CWEC) for Pierre Elliott Trudeau International Airport in Montreal is used as base weather data. The'morphing' method was used to downscale the data from HadCM3 to generate hourly future typical horizon data for the 2020's, 2050's and 2080's decades from CWEC data. In addition, the recorded years of 1968–1987 are morphed (from the HadCM3 data) to generate the Future Meteorological Year (FMY) year-by-year weather data for 2018–2037. *CCWorldWeatherGen* a free Microsoft Excel-based tool developed by the University of Southampton, is used to transform base years into future climate change years, a method similar to that used in [26]. A set of 126 building simulations (126 roof configurations of varying thermal resistance and solar reflectance as discussed in 2.1) were conducted to evaluate the total energy consumption required for cooling and heating for each of the horizon future years and for the future typical years.

3. Results and discussion

3.1. Results from horizon future years

A review of results from a simulation calculated with original CWEC data shown on the left side of Fig. 1 indicate that heating energy consumption is dominant in the total energy consumption balance. As is expected, heating energy consumption is highest when the building roof is simulated with low insulation values, and decreases when insulation is increased as per Fourier's law of heat conduction. Moreover, lower solar reflectance reduces the heating energy consumption.

By contrast, the building's yearly cooling energy consumption is lowest for a roof with high solar reflectance and low insulation, and highest with low reflectance and low insulation. Greater roof insulation reduces cooling energy consumption with low reflectance roofs, but increases it with high reflectance roofs, bridging the difference between albedo configurations. When added together, results show that the highest total energy consumption for this building occurs when solar reflectance and insulation values are low. Results also show that low solar reflectance on the roof is desirable during the heating season and undesirable in the cooling season.

This model is insightful but possesses the inherent flaw that it does not consider the enduring presence of snow, a highly reflective material, on flat roofs in the winter. Snow can therefore significantly increase the solar reflectance of a roof during the heating season. Snow also increases the overall thermal resistance of the roof contributing to less heating energy consumption, no matter with high or low reflective roof. Since snow is never present during the cooling season, it could be reasonable to assume that increasing the solar reflectance of a flat roof could have a positive effect in reducing the overall yearly energy consumption of a building. Furthermore, as is mentioned above, a building's roof is less exposed to sunlight during the winter months as it is during the summer months.

For simulations which were carried out with CWEC weather files that were morphed with GCM data for the 2020's and 2080's horizon years, Fig. 1 – Cooling, heating and total energy for a retail building using CWEC and horizon weather data shows that no matter which roof design is used, in future years, the cooling energy consumption will increase while the heating energy consumption will decrease.

However, some of the designs show smaller variations in the future when compared to CWEC data. To better understand this trend along with the behaviour of different designs, future year-by-year simulations are also conducted.

3.2. Large-scale simulation investigating design alternatives over a long range of future years

Year-by-year simulations from 2018 to 2037 are also made to evaluate the fluctuations of the building energy performance and to identify which designs have the smallest variations.

Future trends for the “four corners” of the simulations, representing the highest and lowest solar reflectance ratios and the highest and lowest insulation values, are represented in Fig. 2. Maximum and minimum total energy consumption years occur in 2022 and 2031 respectively, with an average gap of 20 kWh/m^2.

While outliers of high and low energy years continue to appear, a tendency showing a progressive reduction in heating energy and an increase in cooling energy exists over the simulation period. Fig. 3

CWEC Cooling Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	15	14	14	14	13	13	13	13	13	13	13	13	13	13
0.2	14	14	13	13	13	13	13	13	13	13	13	13	13	13
0.3	13	13	13	13	13	13	13	13	13	13	13	13	13	13
0.4	13	13	13	13	13	13	13	13	13	13	13	13	13	13
0.5	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.6	11	12	12	12	12	12	12	12	12	12	12	12	12	12
0.7	11	11	11	11	12	12	12	12	12	12	12	12	12	12
0.8	10	10	11	11	11	11	12	12	12	12	12	12	12	12
0.9	9	10	10	11	11	11	11	11	11	12	12	12	12	12

2020's Cooling Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	20	19	18	18	18	17	17	17	17	17	17	17	17	17
0.2	19	18	18	18	17	17	17	17	17	17	17	17	17	17
0.3	18	18	17	17	17	17	17	17	17	17	17	17	17	17
0.4	18	17	17	17	17	17	17	16	16	16	16	16	16	16
0.5	17	16	16	16	16	16	16	16	16	16	16	16	16	16
0.6	16	16	16	16	16	16	16	16	16	16	16	16	16	16
0.7	15	15	15	15	16	16	16	16	16	16	16	16	16	16
0.8	14	14	15	15	15	15	15	15	15	16	16	16	16	16
0.9	13	14	14	14	15	15	15	15	15	15	15	15	15	15

2050's Cooling Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	25	24	23	23	22	22	22	22	22	22	21	21	21	21
0.2	24	23	22	22	22	22	22	21	21	21	21	21	21	21
0.3	23	22	22	22	22	21	21	21	21	21	21	21	21	21
0.4	22	22	21	21	21	21	21	21	21	21	21	21	21	21
0.5	22	21	21	21	21	21	21	21	21	21	21	21	21	21
0.6	21	20	20	20	20	20	20	20	20	20	20	20	20	20
0.7	20	20	20	20	20	20	20	20	20	20	20	20	20	20
0.8	19	19	19	19	20	20	20	20	20	20	20	20	20	20
0.9	18	18	19	19	19	19	19	19	20	20	20	20	20	20

CWEC Heating Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	102	94	89	86	83	82	80	79	79	78	77	77	76	76
0.2	103	95	89	86	84	82	81	80	79	78	77	77	76	76
0.3	104	95	90	87	84	83	81	80	79	78	78	77	77	76
0.4	106	96	91	87	85	83	82	80	79	79	78	77	77	77
0.5	107	97	92	88	85	83	82	81	80	79	78	78	77	77
0.6	109	99	93	89	86	84	82	81	80	79	79	78	77	77
0.7	110	100	94	89	87	85	83	82	81	80	79	78	78	77
0.8	112	101	95	90	87	85	83	82	81	80	79	79	78	78
0.9	114	102	96	91	88	86	84	83	81	80	80	79	78	78

2020's Heating Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	89	82	78	75	74	72	71	70	69	69	68	68	67	67
0.2	90	83	79	76	74	72	71	70	70	69	69	68	68	67
0.3	92	84	79	76	74	73	72	71	70	69	69	68	68	68
0.4	93	85	80	77	75	73	72	71	70	70	69	69	68	68
0.5	94	86	81	78	75	74	72	71	71	70	69	69	68	68
0.6	95	87	82	78	76	74	73	72	71	70	70	69	69	68
0.7	97	88	82	79	77	75	73	72	71	70	70	69	69	68
0.8	99	89	83	80	77	75	74	73	72	71	70	70	69	69
0.9	100	90	84	81	78	76	74	73	72	71	71	70	69	69

2050's Heating Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	81	75	71	69	67	65	64	64	63	62	62	62	61	61
0.2	82	76	72	69	67	66	65	64	63	63	62	62	61	61
0.3	83	76	72	70	68	66	65	64	63	63	62	62	62	61
0.4	85	77	73	70	68	67	65	64	64	63	63	62	62	61
0.5	86	78	74	71	68	67	66	65	64	63	63	62	62	62
0.6	87	79	74	71	69	67	66	65	64	64	63	63	62	62
0.7	88	80	75	72	69	68	66	65	65	64	63	63	62	62
0.8	90	81	76	72	70	68	67	66	65	64	64	63	63	62
0.9	92	82	77	73	71	69	67	66	65	65	64	63	63	63

CWEC Total Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	117	108	103	99	97	95	94	92	92	91	90	90	89	89
0.2	117	108	103	99	97	95	94	93	92	91	90	90	89	89
0.3	118	109	103	100	97	95	94	93	92	91	90	90	89	89
0.4	118	109	104	100	97	96	94	93	92	91	91	90	90	89
0.5	119	110	104	100	98	96	94	93	92	91	91	90	90	89
0.6	120	110	104	101	98	96	94	93	92	91	91	90	90	89
0.7	121	111	105	101	98	96	95	93	92	92	91	90	90	89
0.8	122	111	105	101	99	96	95	94	93	92	91	90	90	90
0.9	123	112	106	102	99	97	95	94	93	92	91	91	90	90

Roof Thermal Resistance (m^2K/W)

2020's Total Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	109	101	96	93	91	90	88	87	86	86	85	85	84	84
0.2	109	101	97	93	91	90	88	87	87	86	85	85	84	84
0.3	110	102	97	94	91	90	88	87	87	86	85	85	84	84
0.4	110	102	97	94	92	90	89	88	87	86	85	85	84	84
0.5	111	102	97	94	92	90	89	88	87	86	85	85	85	84
0.6	111	103	98	94	92	90	89	88	87	86	86	85	85	84
0.7	112	103	98	94	92	90	89	88	87	86	86	85	85	84
0.8	113	103	98	95	92	91	89	88	87	86	86	85	85	84
0.9	113	104	99	95	93	91	89	88	87	87	86	85	85	84

Roof Thermal Resistance (m^2K/W)

2050's Total Consumption (kWh/m^2)

Roof Solar Reflectance	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.1	106	99	94	91	89	87	86	85	84	84	83	83	82	82
0.2	106	99	94	91	89	87	86	85	85	84	83	83	82	82
0.3	107	99	94	91	89	88	86	85	85	84	83	83	82	82
0.4	107	99	94	91	89	88	86	85	85	84	83	83	83	82
0.5	107	99	94	91	89	88	86	85	85	84	83	83	83	82
0.6	108	99	95	92	89	88	86	86	85	84	83	83	83	82
0.7	108	100	95	92	89	88	87	86	85	84	84	83	83	82
0.8	109	100	95	92	90	88	87	86	85	84	84	83	83	82
0.9	109	100	95	92	90	88	87	86	85	84	84	83	83	82

Roof Thermal Resistance (m^2K/W)

Fig. 1. Cooling, heating and total energy for a retail building using CWEC and horizon weather data.

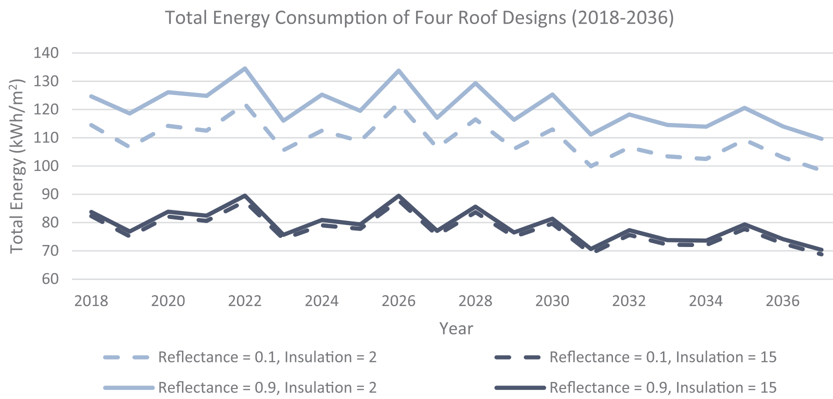


Fig. 2. Total energy consumption for four roof designs from 2018–2037.

shows total energy consumption heat maps for CWEC and extreme future years 2022 and 2031. shows that this method produces total energy consumption results from CWEC data which results in lower consumption than for the extreme simulated weather case possibly occurring in 2022. This difference is explained by the fact that CWEC data represents an average situation taken over 30 years of data and does not include the peaks and valleys that will inevitably occur.

While it is generally anticipated that reduced heating demand and increased cooling demand will be prevalent over the next two decades, the fact that cooling energy consumption increases at a lower rate due to high COP values in cold climates will lead to net reductions in total energy consumption. The figures also indicate that a lower reflectance on the roof reduces total energy consumption at low insulation values, and that the reflectance ratio no longer has any effect at high roof insulation values.

Designers must explore design strategies which will allow buildings to anticipate the effects of climate change. One such strategy involves calculating yearly loads over the useful lives of buildings and designing for their mean. If the changes are assumed to be relatively linear over this period, designs should yield the lowest deviations from base conditions. One advantage of using this strategy is that HVAC equipment can be sized and installed only once and will moderately cover most weather scenarios over the building's lifespan. The downside is that heating and cooling systems will function best in the middle of the building's useful life, and will be over-and under-designed at the beginning and at the end of it, respectively.

Adding to this strategy is the determination of the variance for every design over the same period. All the roof combinations together with corresponding mean and variance of cooling and heating energy consumption of the building for the next 20 years are plotted in Figs. 4 and 5. The bubble colors show the average intensity of future 20 years energy consumption. The variance of energy consumption for 9 designs are shown with the numbers inside the bubbles, and the bubble size indicates the relative scale in variance. The cooling plot indicates that regardless of the insulation value, a high solar reflectance value of 0.9

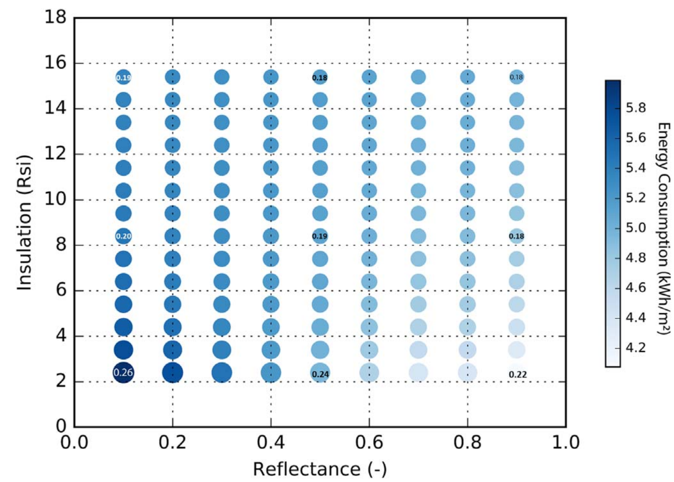


Fig. 4. Mean and variance of cooling energy use for all design combinations for 2018–2037.

will lead to Pareto solutions (minimum mean and minimum variance) over all insulation values. High solar reflectance therefore minimizes the cooling energy consumption and its variance, which improves the robustness of the design. In this case, a flat roof is hit by solar rays and solar radiation becomes the most sensitive parameter. A high solar reflectance factor reduces the effects of solar radiation on energy consumption (as 90% of the solar radiation directed on the roof will be reflected towards the sky), so variations resulting from yearly variations are reduced.

When it comes to heating energy consumption, solar radiation does not play as important a role due to the winter solar angle variation. Thus, the outdoor temperature becomes the more sensitive parameter. Fig. 5 reveals which design combinations lead to ideal situations for low mean heating energy use and variance during that period. This plot indicates that high roof reflectance requires greater energy

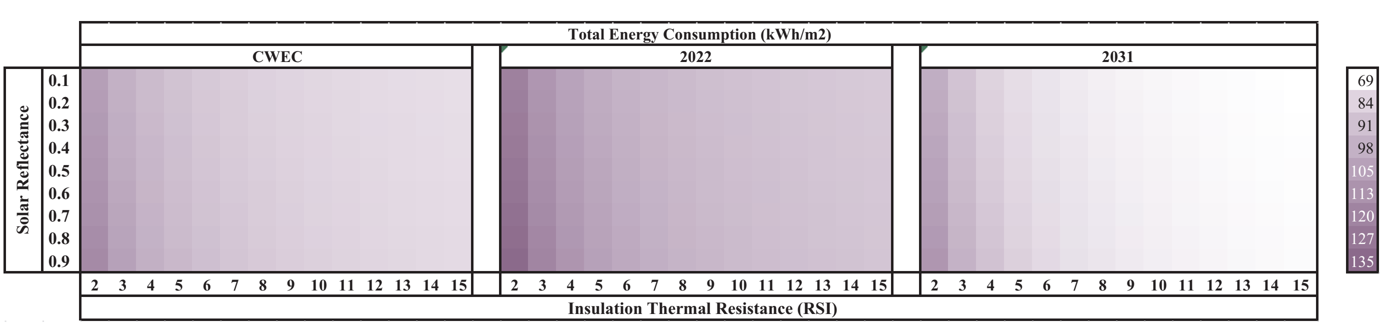


Fig. 3. Total energy consumption heat maps for CWEC and extreme future years 2022 and 2031.

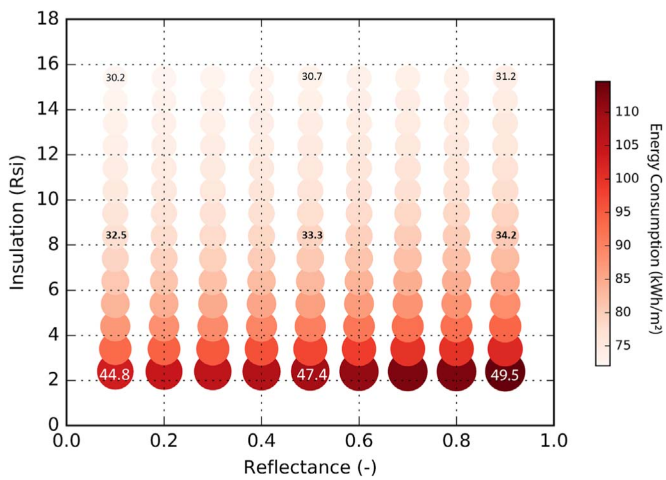


Fig. 5. Mean and variance of heating energy use for all design combinations for 2018–2037.

consumption levels for every insulation value, and that linear increases in insulation resistance provide progressively fewer savings in electrical energy, as per Fourier's heat conductance law.

With higher level of insulation, the heating energy consumption intensity for solar reflectance values of 0.1 and 0.9 almost overlap with relatively close variance. The difference in variance of different solar reflectance can be even negligible if the winter snow is considered. This statement can fall in line with previous studies [7,36,50], in which roof designs with high insulation and high solar reflectance were suggested as optimal designs for a cold climate. Cooling system efficiency can play a significant role in energy performance of the buildings. As in this study, it is assumed that the building is cooled by a cooling system with a COP of 2.93 (an EER of 10.0), which is the ASHRAE Standard 90.1–2003 mandatory minimum requirement for air-cooled air-conditioners with cooling capacities between 70.3 and 222.5 kW (240 and 760 MBtu/h). A COP of 1 can be assumed for the electrical heating system if it is assumed that 100% of the power that is consumed is transformed into useful heat, leaving cooling as a minor factor in total annual energy consumption of the building.

Practically, reflective roof surfaces are relatively simple and inexpensive to implement. Greater insulation however requires greater quantities of expensive materials, increased hours of specialized labor, and finally leads to a thicker roof, which in turn require stronger support systems for a heavier roof. These factors must contribute towards economic decisions which will determine an optimal insulation value in relation to energy costs over a building's lifespan, ideally adjusted for interest and inflation.

There exists another factor which should be considered when designing heating and cooling systems based on mean values from morphed weather data. While it is possible that the useful life of a building (without major renovations) can reach 40 years or more and that its envelope will likely remain the same, much of the critical HVAC equipment will have shorter usable lives. ASHRAE lists estimated lifespans for all types of equipment in its HVAC-R Handbook [51]. ASHRAE estimates that rooftop air conditioners should have a median lifespan of 15 years, gas or electric unit heaters, 13 years, and chillers, 20–23 years. If permanent HVAC systems in the building (such as DX refrigeration lines, air ducts or chilled water circuits) are sized to accommodate future increases or decreases in capacity, it becomes possible to plan for these changes in the scheduled replacement of HVAC equipment. If executed correctly, such a plan can minimize overall heating and cooling energy consumption of the building over its lifespan.

4. Conclusion

The research described in this paper shows that climate change will affect building energy consumption in future years and should be considered when designing HVAC systems today. Selecting reflectance and insulation values for a building roof should imply calculating yearly heating and cooling consumption data over a period covering a building's lifespan to determine optimal configurations.

These results also show that heating energy consumption in a building is significantly reduced with higher levels of roof insulation and that increase in solar reflectance lead to reductions in cooling energy consumption and variance. This indicates that cool roof designs are suitable for robust designs with respects to cooling energy. However, it should be noted that in cold climates like the one in Montreal, flat roofs are covered with snow during many of the heating days which leads to reduced solar effects. For these reasons, increased roof solar reflectance will have a minor effect on a building's heating energy performance in the winter. Therefore, in a robust building energy performance case, the total energy consumption variation will generally be affected by variations in cooling demand. In addition, using cool roofs would be even more attractive when larger scale benefits such as reduction in urban heat island effect is taken into account.

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